Electron cloud buildup and related instability in the CERN Proton Synchrotron

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The beam-induced electron cloud buildup is one of the major concerns for the SPS and the design of the future LHC. During the 2000 run, this effect has also been observed in the PS with the nominal LHC-type beam. The electron cloud induces a baseline distortion in electrostatic pickup signals, both during the last turns in the PS, when the full bunch length is reduced to less than 4 ns, and in the transfer line between the PS and the SPS rings. In the year 2001, modifications in the rf hardware allowed us to study the properties of the beam instability related with the electron cloud phenomenon for a total bunch length of about 10 ns. The complete set of experimental observations carried out in the PS machine is presented and discussed in detail.

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I. INTRODUCTION

Since the first studies concerning the potential harmful effect of the electron cloud buildup in the CERN Large Hadron Collider (LHC) machine (see [1], and references therein), the research shifted from purely theoretical to more experimental activities. After the Proton Synchrotron (PS) complex[1] started to produce and deliver an LHC-like proton beam [3,4], the Super Proton Synchrotron (SPS) machine observed strong electron cloud buildup associated with a vertical instability [5,6]. Intense efforts were devoted to improve the understanding of the complex phenomena by using the SPS as a LHC test bed.

When the nominal LHC beam was generated by the PS machine [7], it was somewhat natural to investigate whether such a machine was also affected by electron cloud phenomena. It turned out that this was the case [8] and the standard signature, baseline drift in electrostatic devices, was observed. In fact, this should not be surprising as both machines work with the same type of beam and their vacuum chambers are quite similar: both are stainless steel pipes (the secondary emission yield is about 1.9) with comparable sizes (140 mm width, 70 mm height for PS and 129, 48.5 mm for SPS, respectively). Furthermore, the electron cloud buildup has also been observed in SPS regions with larger vertical half aperture, up to 70 mm, thus making the similarity with the PS environment even stronger.

Thanks to the clean experimental conditions available in the PS machine, with a stable beam circulating on the high-energy flattop, further studies were devoted to the analysis of a possible electron cloud instability affecting the LHC beam. Interestingly, it turned out that, due to the very principle used to generate such a beam, the instability could not develop.

[1]For a review of the different types of beams normally delivered by the PS complex, see Ref. [2].

The nominal LHC beam at the exit of the PS consists of a train of 72 bunches, each of 1.1×10^{11} protons, spaced by 25 ns and with a momentum of 26 GeV/c. The longitudinal emittance at 2σ is 0.35 eVs (obtained by means of successive longitudinal bunch splitting [9,10]), and the normalized rms transverse ones are 2.5 μm. Just before extraction, the bunches are compressed from $\sim$16 to $\sim$4 ns total length, within about 100 turns (i.e., about 200 μs). This is achieved by bunch rotation after a nonadiabatic increase of the rf voltage. The rotating bunches in the mismatched bucket are ejected after one quarter of the synchrotron period, when the minimum length is reached. A collection of the main parameters of the LHC beam and PS ring is listed in Table I.

However, by using adiabatic rf gymnastics it was only possible to reduce the total bunch length down to 10 ns and then to keep the bunches circulating for about 100 ms.

TABLE I. Main parameters of the LHC beam and PS ring.

Number of bunches	72
Bunch spacing ($T_{\rm sep}$)	25 ns
Bunch population (N_b)	1.1×10^{11} protons
Transverse rms emittances ($\epsilon^*_{x,y}$)	2.5/2.5 μm
Chamber half aperture (x)	70 mm
Chamber half aperture (y)	35 mm
Tunes ($Q_{x,y,s}$)	6.25/6.25/0.0015
Bunch total length ($4\sigma_z/c$)	4 ns
rms-momentum spread	7×10^{-4}
Longitudinal 2σ emittance (ϵ_l)	0.35 eVs
Circumference	628 m
Dipole field (B_{y0})	1.256 T
Field gradient (G)	5.2 T/m
Relativistic γ	27.7
$T_{\rm rev}$	2.2 μs
Average beta functions ($\beta_{x,y}$)	16/16 m
Average dispersion (D_x)	2.56 m
Momentum compaction (α)	0.027
Chromaticities ($\xi_{x,y}$)	up to 0.5 in both planes

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Under these conditions, the beam instability was observed.

In the present paper, the observations made with the LHC-type beam in the PS ring and in the transfer line joining the PS to the SPS are described in Sec. II. In Sec. III the influence on the electron cloud buildup of the longitudinal bunch train structure and solenoidal field is presented. The outcome of the investigations concerning the beam instability is reported in Sec. IV, where also some possible remedies are outlined. Finally, conclusions are drawn in Sec. V.

II. ELECTRON CLOUD BUILDUP

A. PS ring

An electron cloud buildup was observed during the last turns in the PS, when the bunch compression takes place. The electron cloud induces baseline distortions in electrostatic pickup signals. The effect is essentially visible in the vertical plane, as illustrated in Fig. 1. The pickup has the bandwidth 0.2–30 MHz and is located near a combined function bending magnet. These distortions are not present when either the bunch rotation is not active or other beams (i.e., non-LHC-type) are observed.

B. TT2 transfer line between PS and SPS

The electron cloud buildup was also observed in the TT2 (single-pass) transfer line between PS and SPS (see Fig. 2). Here the pickup is located in a field-free region, and its bandwidth is 0.006–400 MHz. The capacitance of the device is $C = 500$ pF and the voltage corresponding to the drift of the baseline is estimated to be $V \approx 300$ mV. Hence the number of electrons pulled out of the electrostatic pickup electrodes is given by

$$n_e = \frac{CV}{e} \approx 10^9. \quad (1)$$

However, in this case electron cloud effects seem to lead only to instrumentation problems: observations indicate that the beam quality, i.e., the beam position and the transverse beam emittance, are not affected. It will be shown later that this is due to the fact that the time of electron cloud-beam interaction is short compared to the rise time of the related instability. All these phenomena are a peculiarity of the nominal LHC beam, i.e., no distortion is visible when observing other beams delivered by the PS.

Finally, it is worthwhile mentioning that electron cloud buildup also perturbs the emittance measurement devices installed in the TT2 transfer line. The standard approach to determine the beam emittance, provided the dispersion function is known all along a transfer line, consists of measuring transverse beam profiles at three different locations [11]. The devices installed in TT2 are secondary emission monitors made of thin wires. In Fig. 3 (left panels) typical horizontal beam profiles for the LHC-type beam without the final bunch rotation are shown. All of them have a nice Gaussian-like shape. However, when the bunch rotation is turned on, beam profiles are strongly perturbed (see the right panels of Fig. 3).

A clear nonzero signal is present even when the monitors are retracted from the beam, provided the bunch rotation is active. Of course, no signal is present in the absence of bunch rotation (no electron cloud buildup) and with the monitors out of beam. No disturbance of the beam profiles is present with bunch rotation but larger bunch spacing (e.g., 50 ns) or with a reduced bunch intensity.

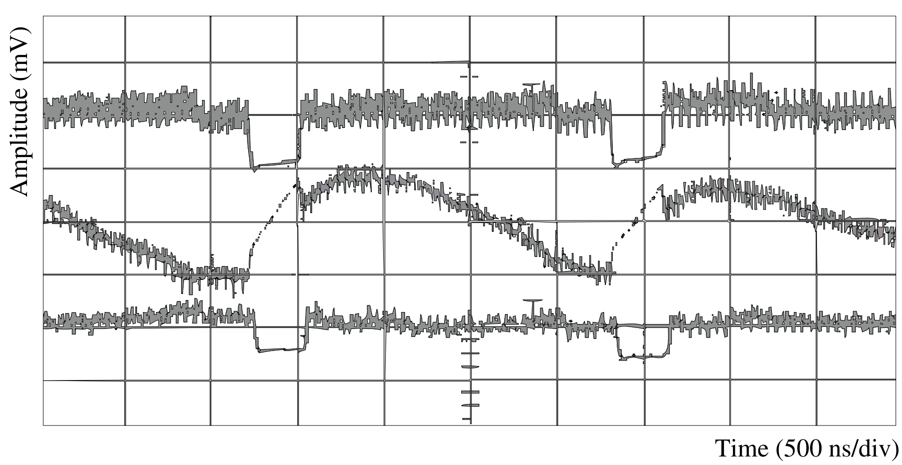

FIG. 1. Measured baseline drift in a PS electrostatic pickup during bunch compression prior to extraction. From top to bottom: Σ (300 mV/div), Δy (20 mV/div), and Δx (200 mV/div). The 30 MHz bandwidth of the pickup does not allow discriminating the 4 ns long bunches. The bunch train lasts 1.8 μs and the gap is 320 ns.

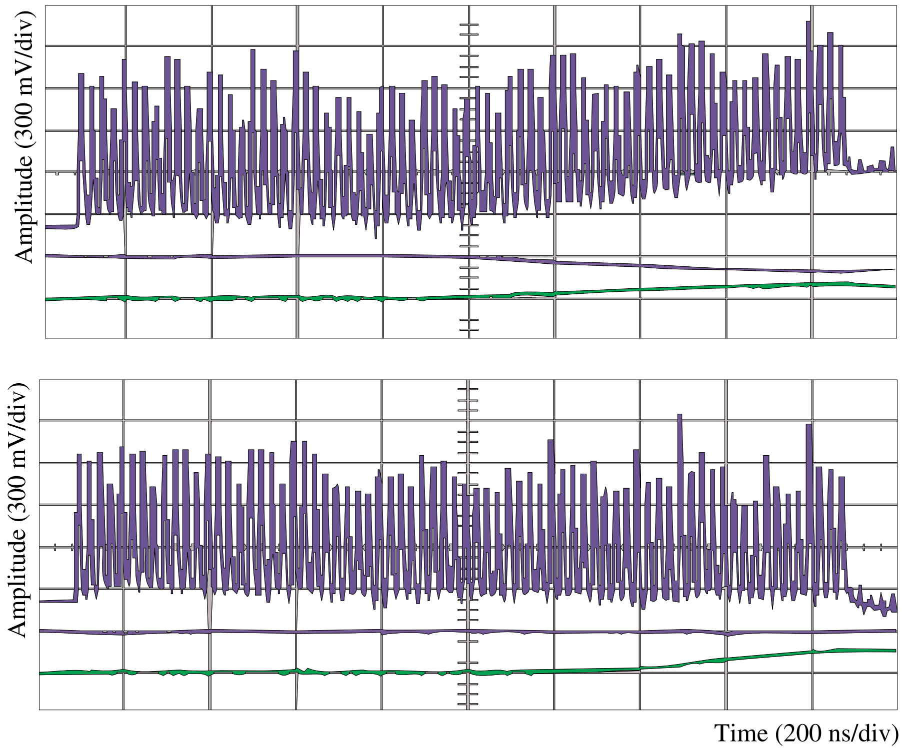

FIG. 2. (Color) Measured baseline drift in a TT2 electrostatic pickup: $I_{\text{solenoid}} = 0$ (upper panel) and $I_{\text{solenoid}} = 10$ A (lower panel). The details of the solenoid will be discussed in Sec. III C. From top to bottom: Σ, Δx, and Δy (Δx, Δy signals almost coincide with the grid lines). This pickup has a bandwidth wide enough to allow discriminating the short bunches. Such a structure is not observable on Δx and Δy signals as the beam is centered in the pickup.

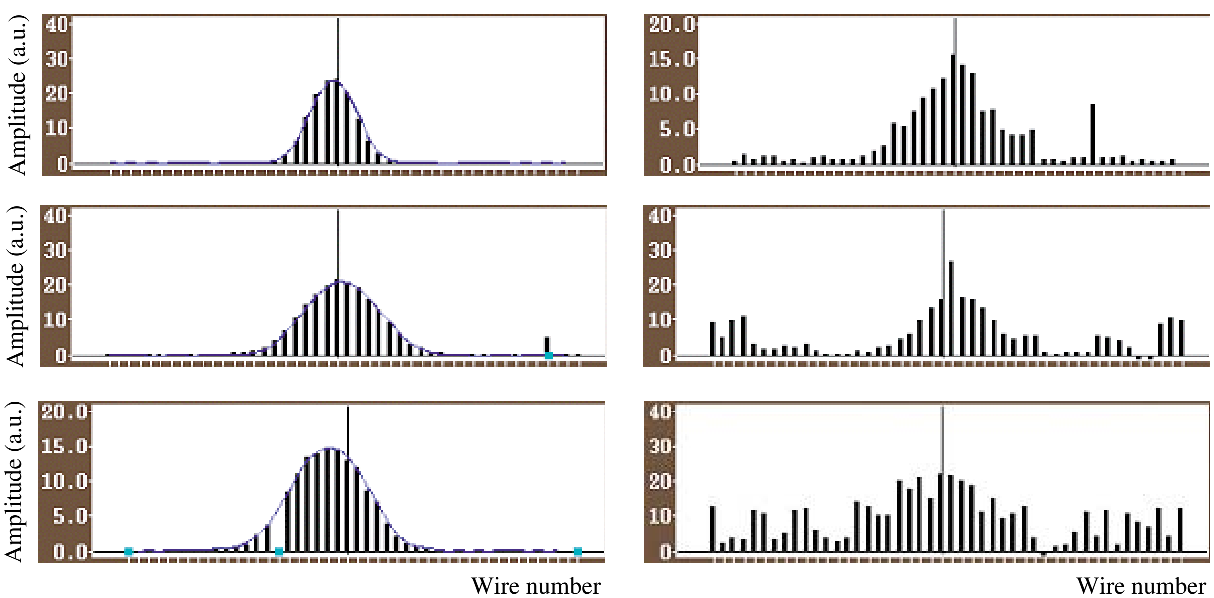

FIG. 3. (Color) Transverse horizontal beam profiles measured with secondary emission monitors at three different locations in the TT2 transfer line. The measurements performed without bunch rotation are shown on the left, while the profiles on the right are obtained with the final bunch rotation active. The wire spacing is 0.5 mm for all the monitors except the central one where the spacing is 0.35 mm.

III. CONTROL OF ELECTRON CLOUD BUILDUP

The buildup of an electron cloud can be either suppressed or strongly reduced by acting on a number of physical parameters. Observations were made of the dependence on the bunch spacing and on the presence of gaps in the bunch train. Furthermore, the effect of a solenoidal field on the dynamics of the electron cloud was also studied.

A. Bunch spacing

A variant of the nominal LHC beam with a larger bunch spacing, 50 ns instead of 25 ns, was tested during the years 2000 and 2001. Originally, the presence of strong longitudinal coupled bunch instabilities made it impossible to achieve the nominal intensity per bunch. After a series of improvements on the high order mode of the rf cavities [12], it was possible to obtain the nominal beam intensity, namely, $N_b \approx 1.1 \times 10^{11}$ protons per bunch (p/b), during the 2001 run.

The signals detected on a pickup in the PS machine (upper panel) and in the TT2 transfer line (lower panel) are shown in Fig. 4. Under these conditions the electron cloud buildup is substantially reduced: not only is the baseline drift in the Σ signal smaller than for the 25 ns case, but it also starts later along the bunch train.

B. Gaps in the bunch train

The evolution of the baseline drift in a TT2 electrostatic pickup is depicted in Fig. 5, where gaps of 12 bunches (corresponding to 320 ns) are introduced. The gap is obtained by removing one PS Booster bunch at PS injection. Electron cloud buildup always shows up at the end of the bunch train, independently of the gap position. These measurements show that a gap of 320 ns is not sufficient to reset the memory of the electron cloud: the electron cloud density is rapidly reestablished behind the gap.

Observations performed in the presence of six gaps of 120 ns are shown in Fig. 6. Even in this case a drift of the baseline is visible at the end of the bunch train.

Finally, the case of 84 bunches filling 84 buckets at harmonic number $h = 84$ was also studied. The signals are shown in Fig. 7, where the measurements made with a pickup in the last turns in the PS machine (upper panel) and in the TT2 transfer line (lower panel) are shown.

The buildup of the electron cloud is the strongest among the different cases considered here. Yet, even

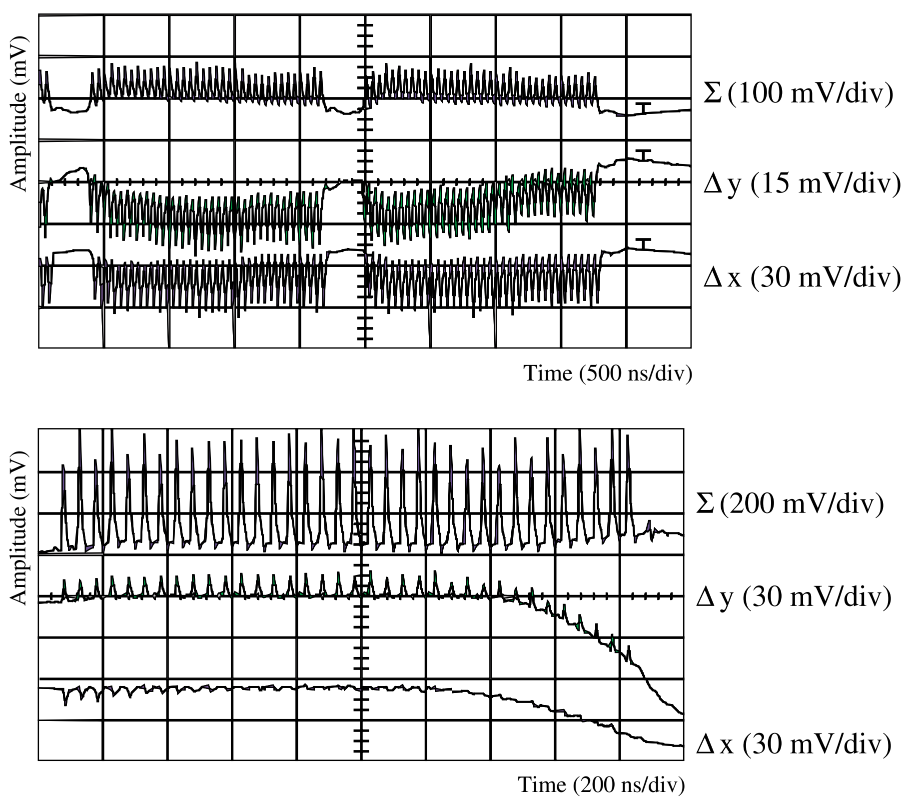

FIG. 4. Measured baseline drift in a PS electrostatic pickup (upper panel) and in TT2 (lower panel) for the 50 ns spacing LHC-type beam. The electron cloud buildup is delayed with respect to the 25 ns case and the drift is also reduced.

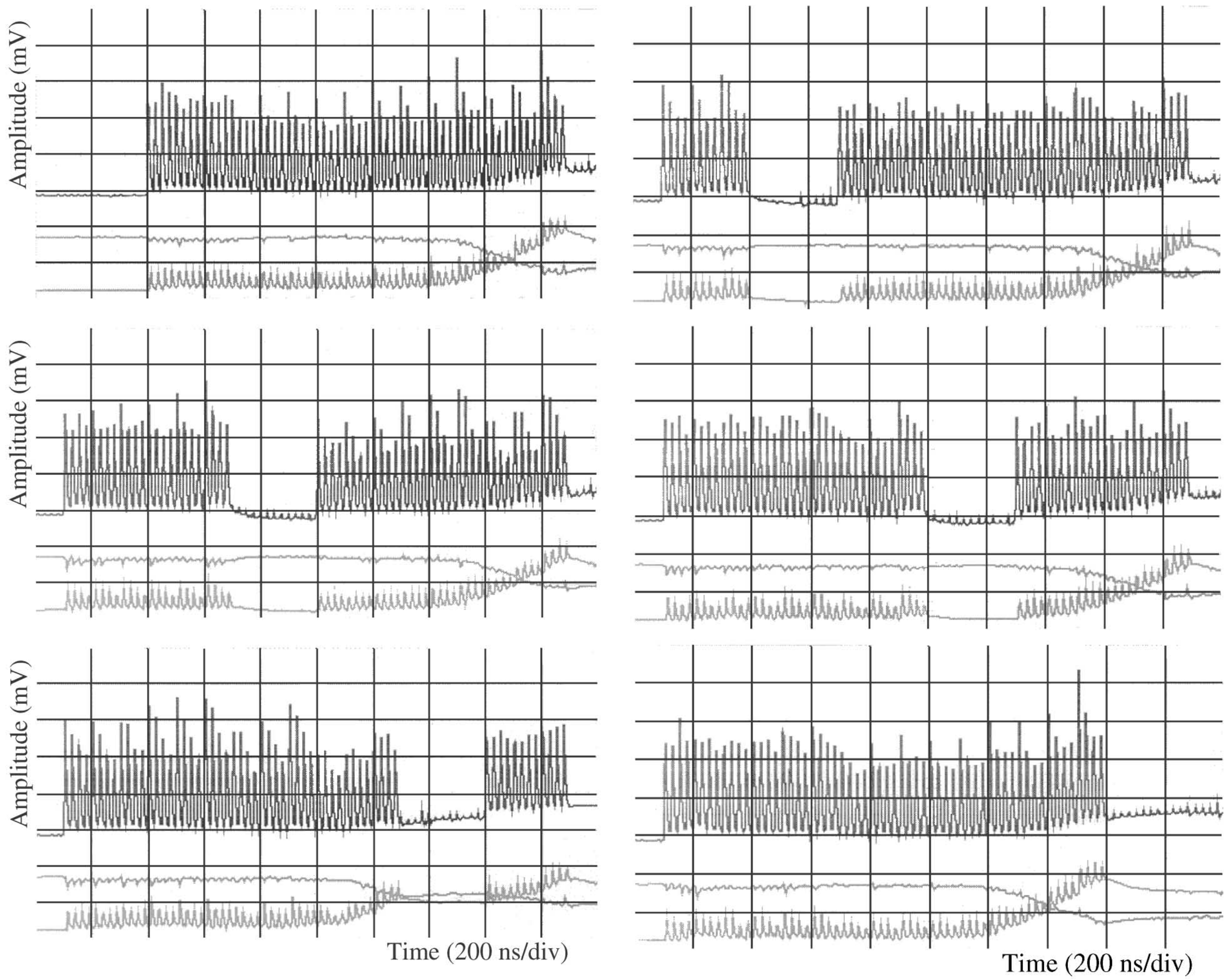

FIG. 5. Measured baseline drift in a TT2 electrostatic pickup, with 6 possible cases of 12 missing bunches. From top to bottom: Σ (800 mV/div), Δy (100 mV/div), and Δx (100 mV/div).

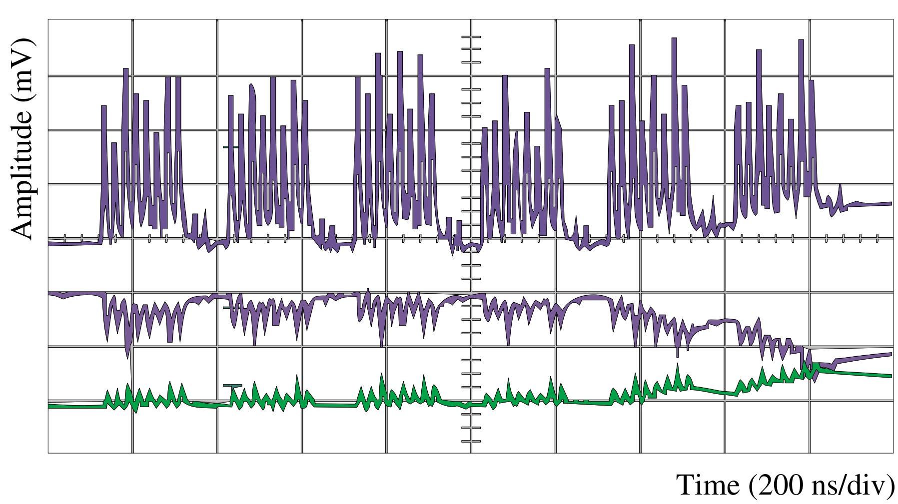

FIG. 6. (Color) Measured baseline drift in a TT2 electrostatic pickup with six gaps of 120 ns. From top to bottom: Σ (300 mV/div), Δx (50 mV/div), and Δy (50 mV/div).

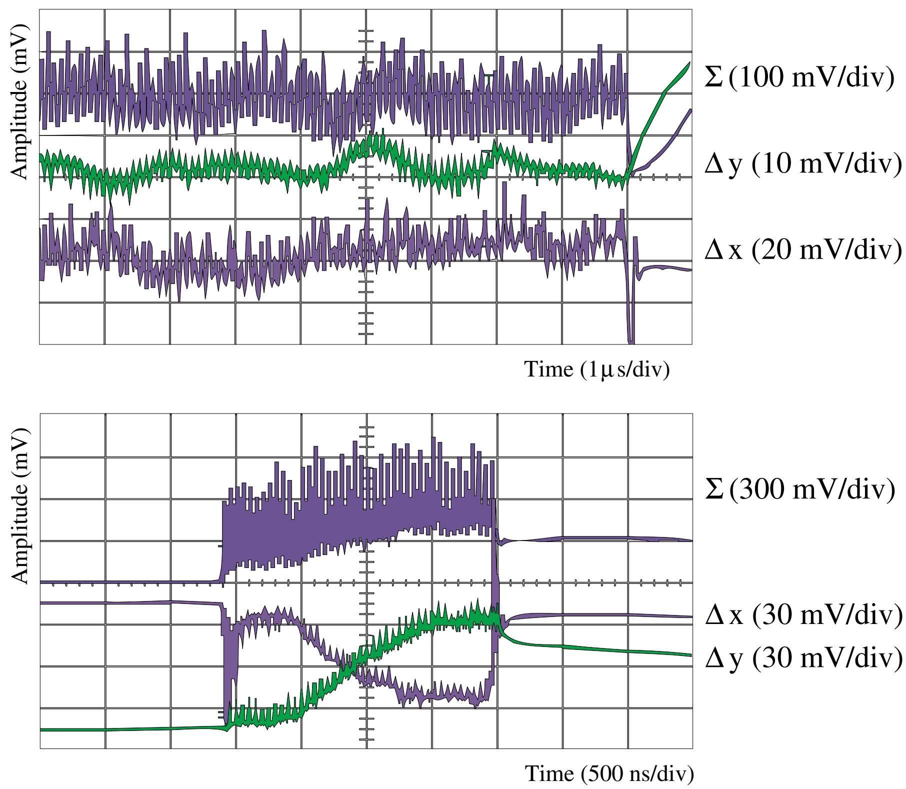

FIG. 7. (Color) Measured baseline drift in a PS electrostatic pickup in the last turns before extraction (upper panel) and in TT2 (lower panel) for the 25 ns spacing with 84 bunches (i.e., no gap). A strong electron cloud buildup is clearly visible. The spike on the Δx signal for the TT2 pickup is generated by the bunches badly ejected due to the finite rise time of the extraction kicker.

under these extreme conditions, which were obtained for only a fraction of a millisecond, the beam was stable.

C. Solenoidal field

The investigations related to the electron cloud buildup in the B-factories and lepton rings, such as KEKB, PEP-II, and BEPC, clearly showed the beneficial effect of the solenoidal field on the machine performance (see Refs. [13–15]). In fact, the longitudinal solenoid field, although quite small, keeps the electrons close to the chamber wall and thus suppresses the beam-induced multipacting.

Hence, the same technique was applied in the TT2 transfer line to confirm the hypothesis that the source of the perturbations of the beam diagnostics was really the electron cloud buildup. To this end, coils were installed at both ends of the wide-band electrostatic pickup. Each of the coils is made of 80 windings over a length of about 0.08 m. The coils have an inner diameter of about 0.13 m and an outer one of about 0.25 m. The distance between the two extreme ends of the coils is 0.4 m, while the longitudinal size of the pickup is about 0.16 m. The maximum current is 10 A. The pickup, together with the additional coils used to generate the solenoidal field can be seen in Fig. 8.

The value of the longitudinal component of the magnetic field along the axis of the pickup is shown in Fig. 9.

By applying a weak solenoidal field in the TT2 electrostatic pickup, the baseline distortion could be eliminated (see Fig. 2). A residual effect is visible, however, on the vertical signal, which may be due to the nonideal solenoidal field created.

IV. INSTABILITIES

A. Experimental observations

After having detected the electron cloud buildup, the next step consisted in studying the related instability in more detail.

It was already clear that for the nominal LHC beam the electron cloud only perturbed the beam diagnostics, the beam quality being unaffected. Hence, a different approach was used where the method of producing the beam was modified. Instead of applying a nonadiabatic

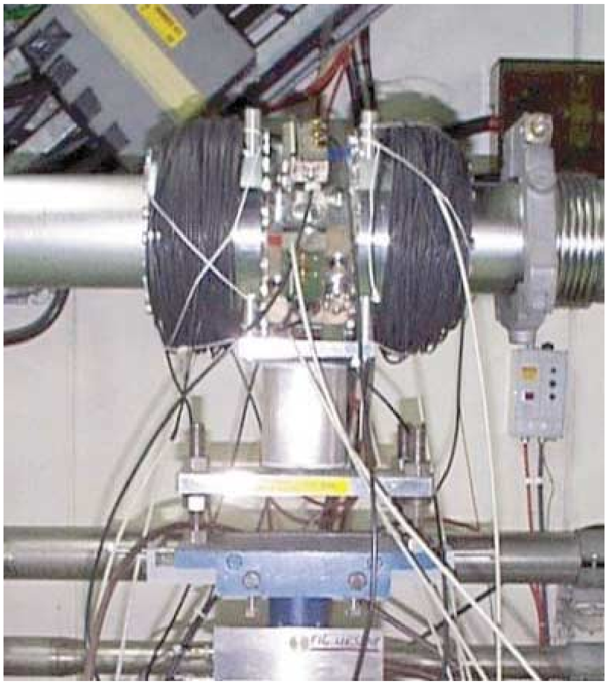

FIG. 8. (Color) View of the electrostatic pickup installed in the TT2 transfer line. The two coils are clearly seen on both sides of the device.

bunch rotation by using 80 MHz cavities on top of the 40 MHz, an adiabatic rf gymnastics was used.

The signal of a horizontal pickup in the PS ring was frequency analyzed to keep track of the evolution of the first unstable betatron line (about 357 kHz). It was possible to observe a horizontal single-bunch instability with a threshold at $N_b^{th} \approx 4.6 \times 10^{10}$ p/b and a rise time of 3–4 ms above the threshold. In Fig. 10 such a signal is shown for six different values of N_b. All the plots cover a time interval of 200 ms before beam extraction. The first case refers to an intensity just below the threshold, while the second one is just above it. The rise time is higher than in the other cases, but this is due to the fact that the measurement is taken near the threshold. The linear amplitude increase in the logarithmic scale is clearly visible in five out of the six cases plotted in Fig. 10.

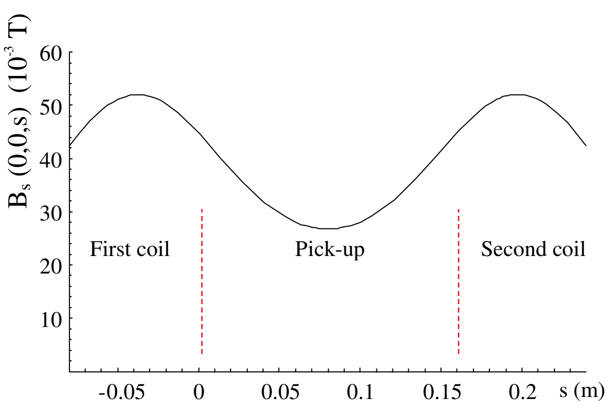

FIG. 9. (Color) Absolute value of the longitudinal component of the magnetic field $B_s(0, 0, s)$ generated by the two coils installed at both ends of the wide-band electrostatic pickup for the maximum current.

It is clearly seen how the instability rise time is almost constant above the threshold. However, the instability appears earlier in time. During the 200 ms shown in the plots the beam undergoes a double-splitting gymnastics (lasting about 55 ms), then it stays with a bunch length of 16 ns for about 40 ms before being adiabatically compressed, reaching a bunch length of about 10 ns in 5 ms. Finally, the bunches are in equilibrium during the last 100 ms before extraction. Therefore, it seems that for the highest intensities the electron cloud buildup occurs already for bunches longer than 10 ns: in fact, the multipacting regime is originated by the interplay of both bunch intensity and bunch length.

Some additional information for the case $N_b \approx 5.5 \times 10^{10}$ p/b is shown in Fig. 11. Together with the evolution of the first unstable betatron line (upper left panel), the Fourier analysis of the same signal is shown in the upper right panel. In the lower part, the signals from pickups in the PS ring (left panel) and TT2 transfer line (right panel) are shown.

It is clear that (i) the strong instability is visible only in the horizontal plane, and (ii) no regular pattern can be detected in the horizontal position along the bunch train. This seems to rule out a multibunch instability.

Two points should be stressed: first, the PS lattice is made of combined function magnets (dipole field with quadrupole component); second, the fraction of machine circumference occupied by the combined function elements is about 70%. Therefore, it is clear that the characteristics of the beam instability will be dictated by the properties of the electron cloud in the main magnets. In addition, due to the peculiar field configuration of a combined function magnet, the property that the wake field in the horizontal plane is close to zero, as for a vertical dipole field, no longer holds true [16], which may explain why a horizontal instability can develop.

B. Remedies

Before going into more details in the analysis of the remedies to be applied to combat the electron cloud driven instability, it is necessary to stress that two different phenomena have to be distinguished: the electron cloud buildup and the instability. Electron cloud buildup from beam-induced multipacting occurs only if the bunch intensity is high enough so as to accelerate electrons to energies of about 100 eV, near the maximum of the secondary emission yield. As far as the instability is concerned, it can occur only if the electron cloud is produced. Therefore, one could conclude that all the remedies discussed in previous sections to prevent the

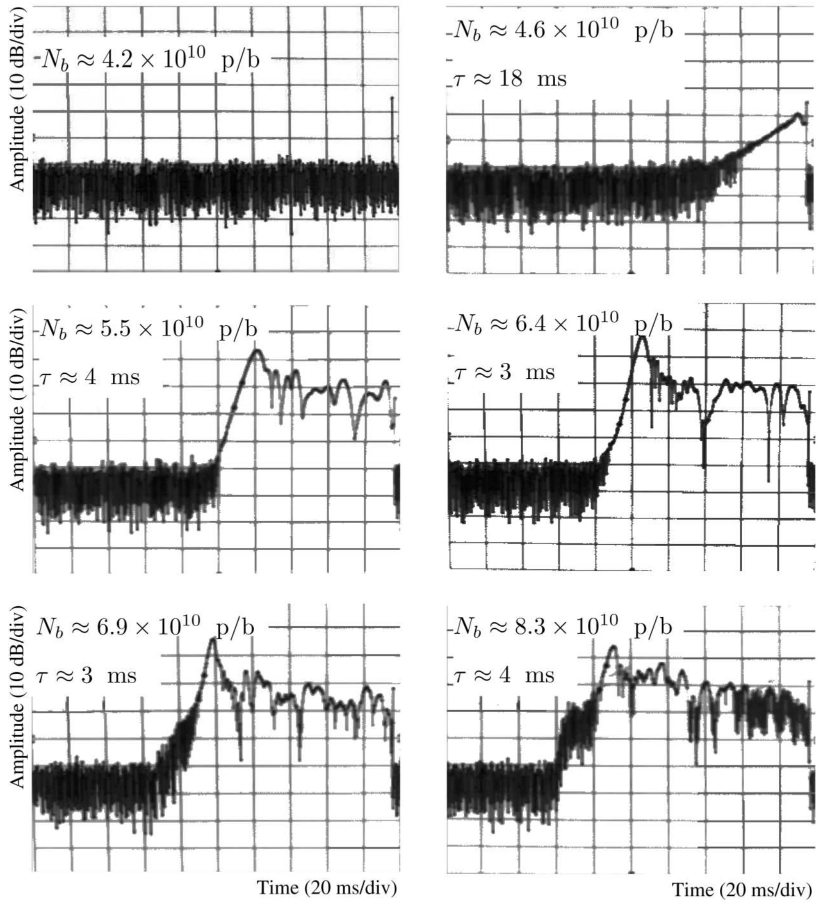

FIG. 10. Rise time of the horizontal instability as a function of the bunch intensity. The signal is obtained with a spectrum analyzer with zero frequency span and a central frequency 357 kHz. The beam is extracted at the end of the horizontal scale.

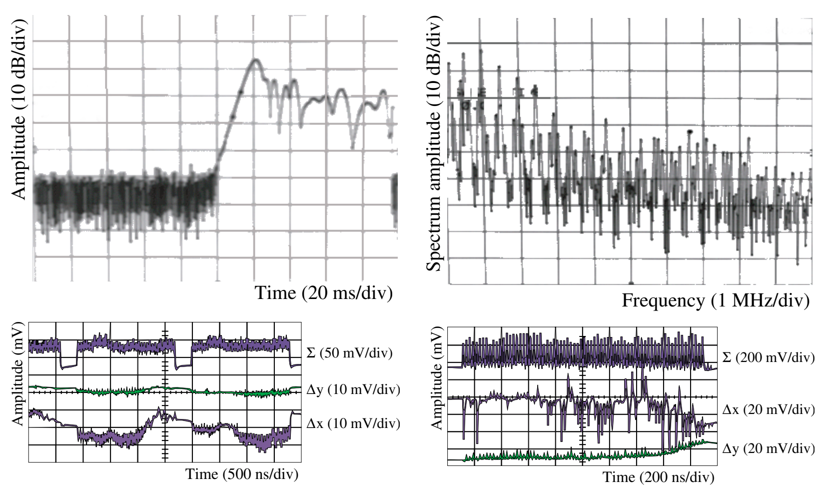

FIG. 11. (Color) Instability footprint for $N_b \approx 5.5 \times 10^{10}$ p/b. The signal obtained via a spectrum analyzer with zero frequency span and central frequency of 357 kHz is shown in the upper left panel. A Fourier analysis from 0–10 MHz is shown in the upper right panel. In the lower part, the signals from a pickup in the PS ring some tens of milliseconds before extraction (left panel) and the TT2 transfer line (right panel) are shown.

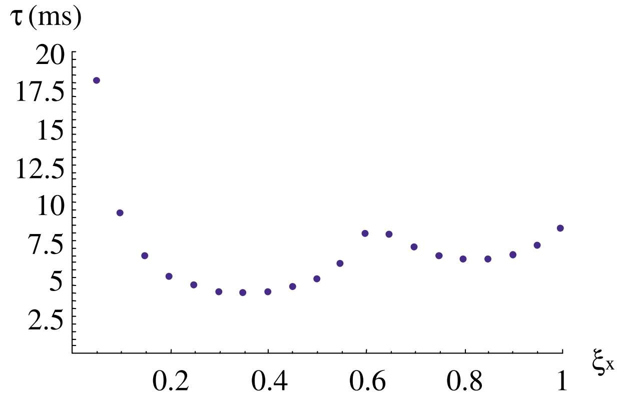

FIG. 12. (Color) Dependence of the horizontal head-tail instability rise time τ on the horizontal chromaticity ξ_x for the theoretical model of the PS.

electron cloud buildup are, in a certain sense, also remedies for the instability. However, here we will discuss the techniques that can be applied to stabilize the beam once the cloud is generated and the beam becomes unstable.

As a first attempt, the horizontal chromaticity ξ_x, defined as

$$\xi_x = \frac{\Delta Q_x}{Q_x} / \frac{\Delta p}{p_0}, \tag{2}$$

where Q_x is the horizontal betatronic tune, p the particle's momentum, and p_0 the reference particle's momentum, has been changed. Normally it is set to about 0.1 on the high-energy flattop. However, similarly to what was done in the SPS [5], ξ_x was increased up to $\xi_x \approx 0.5$, but no variation in the instability rise time was detected.

This fact is in good agreement with theoretical estimates [17] obtained by approximating the electron cloud with a broadband impedance [18] and using the amplitude of the horizontal wake field computed for the PS main magnet [16]. The resulting instability rise time τ as a function of ξ_x is shown in Fig. 12: the weak dependence of τ on ξ_x in the range $0.15 \leq \xi_x \leq 0.5$ is clearly seen.

Finally, octupoles were powered in an attempt to stabilize the beam. Under these new conditions, only a marginal effect was observed, despite the rather large current used (almost near to the maximum sustainable by the power converter). The corresponding octupole-induced tune spread at half width half height [19,20] can be estimated to be $\Delta Q_{x,\mathrm{HWHH}} \approx 4 \times 10^{-5}$ and $\Delta Q_{y,\mathrm{HWHH}} \approx 5 \times 10^{-5}$.

V. CONCLUSIONS AND OUTLOOK

Since generating the required LHC beam in the PS, intense experimental efforts were devoted to measuring electron cloud buildup and related instabilities. As far as the nominal beam is concerned, the conditions to generate an electron cloud buildup are met only when no time is left for the related instability to develop. This is due to the specific rf manipulation, a nonadiabatic bunch rotation performed a few turns before beam extraction.

However, it was possible to study the buildup both at extraction in the PS ring and in the transfer line between the PS and SPS, as a function of some bunch parameters such as bunch spacing, gaps in the bunch train, and presence of a solenoidal field around an electrostatic pickup.

These observations lead to the conclusion that, for the nominal LHC beam, the electron cloud buildup does not alter the beam characteristics. Such a cloud only constitutes a perturbing effect for the different types of beam diagnostics, such as electrostatic pickups and secondary emission monitors.

By introducing a modified rf gymnastic (an adiabatic bunch rotation reducing the bunch length from 16 to 10 ns), it was possible to keep the shortened beam circulating for about 100 ms. Under these conditions, it was possible to observe a horizontal single-bunch instability with threshold $N_b^{\mathrm{th}} \approx 4.6 \times 10^{10}$ p/b, and rise time τ of about 3–4 ms above threshold. No sign of instability was observed in the vertical plane. This seems to be linked to the peculiarity of the PS lattice whose main magnets are combined function magnets. According to preliminary numerical simulations, the main wake field is produced in the horizontal plane. The observations could be explained by the head-tail formalism.

The influence of chromaticity was measured, revealing only a marginal effect on the beam dynamics, in agreement with theoretical predictions. Finally, the effect of octupoles was also tried out, showing only a small stabilizing effect. It is worth mentioning that a variant of the nominal LHC beam with a 50 ns bunch spacing completely removed the instability.

Additional measurements are foreseen for the year 2002 run, to get more quantitative results on the properties of the beam instability related to the electron cloud buildup.

ACKNOWLEDGMENTS

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